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GLACIOLOGICAL AND VOLCANOLOGICAL STUDIES IN THE WRANGELL MOUNTAINS, ALASKA

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16. Abstract The feasibility of applying ERTS data to the study of volcanological and glaciological-phenomena in the Wrangell Mountains has been established. Short term changes at the 4000m summit of Mt. Wrangell (62°N; 144°W), produced by deposition of new snow and its subsequent melting by volcanic heat, can be observed directly on ERTS photographic images at scale of 1:1,000,000. Long term changes in the total amount of exposed rock caused by increasing heat flux at the summit over the past decade can also be observed. Digital printouts of data over selected areas of the summit region provide maps at scale of about 1:20,000 with sufficient detail to follow significant changes. When using photographic images band 7 proved best. When using digital printouts band 7 was best for high contrast scenes, but band 5 was best for low contrast scenes. Large scale glacier features in the Wrangell Mountains can also be successfully studied by ERTS imagery. The most exciting aspect of this study is the fact that changes produced by volcanic activity in craters at the summit of Mt. Wrangell can be directly observed on the ERTS photographic images, and can be followed in detail by using digital forms of the data. Routine satellite monitoring combined with annual aerial photogrammetry provide an adequate observation system for the potentially hazardous and potentially useful Wrangell Mountains.

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The objectives of this project were to determine the feasibility of applying ERTS data to the study of: (1) volcanic activity at the 4000m summit of Mt. Wrangell, Alaska (62°N; 144°W) and (2) large-scale glaciological phenomena in the Wrangell Mountains. Photographic images of ERTS data at scale 1:1,000,000 were cataloged and studied visually and with aid of the color comparative viewer. Digital printouts of data from selected regions of the summit were also made and examined. Supplementary data were obtained in the form of vertical aerial photography together with observations and photography made from light aircraft and an actual field trip to the summit.

Short term changes at the summit of Mt. Wrangell, produced by deposition of new snow and its subsequent melting by volcanic heat, can be observed directly on ERTS photographic images at scale of 1:1,000,000. Band 7 is best for this. Long-term changes in the total amount of exposed rock caused by increased heat flux over the past decade can also be observed. The use of digital printouts from band 7 for high sun angle scenes, and band 5 for low sun angle scenes, yields maps of the summit region at a scale of about 1:20,000 with sufficient detail to follow significant changes. Stereoscopic aerial photographs from NASA aircraft NP3 were used to confirm our interpretations of features at the summit and in the region adjacent to glacier termini. The use of several spectral bands proved useful in allowing positive interpretation of drainage features near the terminus of glaciers and in working with digital printouts of the summit region.

The study of glaciers and volcanic activity by remote sensing in the Wrangell Mountains should continue and be expanded in scope to include annual aerial photography and photogrammetric map making of selected areas. This is especially important as long as the increase in volcanic activity continues at the summit of Mt. Wrangell. Some specific recommendations on the type of research needed are made in Chapter V.

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I. INTRODUCTION

A. General Background

The observational capabilities of the ERTS program introduce the possibility of monitoring volcanic activity at any point on planet Earth. Of special interest are those volcanoes which are snow covered. If the melting of snow and glacier ice by volcanic heat can be observed and measured, it offers a potential means of measuring the volcanic activity which produces the melting. The use of individual snowfalls as calorimeters has been explored in Yellowstone Park (White, 1969). One of the main objectives of the present study is to examine the interaction between volcanic heat and glacier ice in mountains located at high latitudes.

Mt. Erebus in Antarctica and Mt. Wrangell in Alaska are the extreme southern and northern active volcanoes associated with the rim of the Pacific ocean. Both are mantled with glacier ice and have perennial dry snow at their summits. They have been discussed as sites for comparative glaciological studies in the two polar regions (Benson, 1967). A brief comparison of these two locations follows:

	Maximum Altitude	Altitude range around Summit craters	Geographic coordinates	Mean Annual temperature at Summit
Mt. Erebus	3794 m	3600 - 3700 m	77°30'S.;167°E	-27°C
Mt. Wrangell	4317 m	4000 - 4300 m	62°N.; 144°W	-20°C

The mean annual temperature at the summit of Mt. Wrangell is based on the snow temperature 10 m below the snow surface at the center of the Caldera. The mean annual temperature at the summit of Mt. Erebus was calculated from the 700 mb temperature data over McMurdo Sound which is 40 km away from Mt. Erebus.

The pattern of heat flow has changed and the magnitude of heat flux has increased at the summit of Mt. Wrangell during the decade 1960-1970 (Benson, Bingham and Wharton, 1971). This has been noted especially since 1964 (the year of the great Alaska earthquake) by a significant decrease in the mass of glacier ice in the north part of the caldera. Horizontal and vertical components of glacier flow were measured in the caldera and North Crater during 1961 and 1965. In 1966, the anomalously large vertical component was attributed to a nonequilibrium increase in the volcanic heat flux (Bingham, 1967). Similar observations are not available from Mt. Erebus; however, molten lava was visible in its summit crater during November 1973 (Treves and Kyle, 1974).

B. The Original Proposal and its Modifications

As originally submitted to NASA, this proposal had three primary objectives:

1. to develop methods of monitoring volcanic activity in the summit area of Mt. Wrangell.

2. to study the applicability of the ERTS-1 imagery to the study of glaciological problems over the entire Wrangell Mountains, with emphasis of the utility of the repetitive synoptic aspect of the satellite imagery to the study of processes which are active over large areas.

3. to conduct comparative studies between Mt. Wrangell and Mt. Erebus in Antarctica as a step in the general direction of studying comparative processes in polar regions.

In final form, however, the objectives of the project were modified significantly. The project was approved by NASA with exception of the part dealing with Mt. Erebus. This was especially because of the impossibility of locating data collection platforms on Mt. Erebus. However, there was also some question about whether or not any imagery data would be available from Antarctica. Also because of funding limits placed on the entire University of Alaska program it was necessary to restrict the funds for this project. At one stage of planning this project was considered for complete elimination because no thermal infrared (IR) was available on the ERTS-1 satellite. However, the project was too important for deletion, especially because we knew that changes in volcanic activity were taking place at the summit of Mt. Wrangell. Finally a total of $6,000 was allocated to do feasibility studies. This is a very small amount of money and it was justified upon the assumption that thermal IR instrumentation would be available on the ERTS-B satellite, and that this project could be deferred until the ERTS-B satellite was put into orbit.

In summary, the objectives were changed to include only a feasibility study of the applicability of ERTS imagery to: (1) monitoring volcanic activity at the summit of Mt. Wrangell and (2) the study of largescale glaciological phenomena in the Wrangell Mountains. Several aspects of the project were eliminated: (1) the comparative study between Mt. Wrangell and Mt. Erebus and (2) the use of data collection platforms on Mt. Wrangell as well as on Mt. Erebus.

C. History of Research on Mt. Wrangell

1. 1953, 1954

During 1953 and 1954 an expedition to study cosmic rays at high altitude operated at the summit of Mt. Wrangell. It was carried out jointly by the University of Alaska and New York University. Three members of that expedition are currently Professors in residence at the University of Alaska (Drs. R. Elsner, F. Milan and C. Wilson). University of Alaska President Emeritus, T. Moore made the first landing with a ski-equipped Super Cub and supported the group with many flights during the two field seasons. A camp consisting of two Jamesway Huts was built with Air Force support on "hut ridge", a portion of the southern-rim of the North Crater. A report on this expedition was presented by Beiser (1953).

2. 1961

In 1961 glaciological and volcanological research was begun in the summit cladera and surrounding craters. It was based from a temporary tent camp on and near hut ridge, and made some use of the remains of the Jamesway huts put up in 1953. (The huts had been filled with snow, which turned to ice by action of volcanic heat, so they consisted of half-cylinders of ice wrapped in wind-torn canvas.) The main results of the 1961-1962 field work was as follows:

(a) Snow temperature, density, hardness and stratigraphic profiles were measured in 5 pit studies 3-6 m deep with core drilling to depths of 20 m in the snow and firn of the Caldera and North Crater at the summit.

(b) The horizontal component of glacier flow was measured on a network of stakes in the Caldera.

(c) Temperature measurements were made in exposed sand and ash along hut ridge and the calculated heat flux values were 900 to 1800 μ cal cm^{-2} sec^{-1}, i.e. three orders of magnitude greater than the average for the planet.

3. 1962, 1963, 1964

During 1962 field work was curtailed by weather and logistics problems but some observations were made on the stake network established in 1961. It was recognized that tents were not an adequate base camp for extended field work. (All three tents used in 1961 were destroyed by wind and new snow accumulation.) The idea of using volcanic heat in a properly designed base camp was developed as a result of the 1961 measurements. As part of the planning effort the temperature profiles measured in the sand and ash during 1961 were remeasured during field trips in December 1963 and February 1964. A volcanically heated hut was finally built in 1964 on the west end of hut ridge in cooperation with the U. S. Air Force, Arctic Aeromedical Laboratory, Aerospace Medical Division, and the U. S. Army Arctic Test Center (Chauvin, 1965).

4. 1965, 1966

In 1965 and 1966 an extensive glaciological-volcanological program was carried out at the summit of Mt. Wrangell:

(a) Pit studies, with core drilling, were made in the Caldera and North Crater.

(b) The mean annual temperature of the snow (10 m below the surface) at the summit is -19°C. The temperature within 1 m of the surface in bare ground areas is +86°C (i.e. the boiling point of water at 600 mb pressure).

(c) The rate of snow accumulation between July 1961 and July 1965 at the summit was 130 cm water equivalent per year in the caldera.

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(d) Vertical and horizontal velocity components were measured on a network of 75 stakes set up in the Caldera and North Crater.

(e) The vertical component was anomalously greater than can be accounted for without attributing it to non-equilibrium increases in volcanic heat flux. This was especially apparent in the North Crater.

5. 1967 to 1971

We continued to observe activity at the summit of Mt. Wrangell and our interpretation (Bingham, 1967) of increasing heat flux proved valid. The changes are especially obvious in the North Crater.

6. 1961 to 1971 Summary

The results of work done during this time interval have been presented in nine papers, (Benson, 1963; Benson and Forbes, 1965; Benson et al., 1965; Wharton, 1966; Bingham, 1967; Furst, 1968; Benson, 1968; Bingham and Benson, 1968; Benson, Bingham and Wharton, 1971). In April 1971 we proposed to utilize the Earth Resources Technology Satellite (ERTS) in the study of Mt. Wrangell.

7. 1972, 1973, 1974

The ERTS-1 project on Mt. Wrangell was carried out, under a very minimal budget, as a feasibility study of the applicability of ERTS imagery to the study of the Wrangell Mountains. It was Contract No. NAS 5-21833, Task No. 11, Project No. 110-M. Data coverage extended from 2 August 1972 to 13 August 1973. It included 38 scenes beginning with 1010-20331 and ending with 1386-20220. However, an additional 12 scenes were analyzed from the period 14 August 1973 to 5 April 1974 (1387-20275 to 1621-20230), together with one scene over Mt. Erebus (24 December 1972, 1154-19322), which was purchased from the Sioux Falls ERTS headquarters. The present report summarizes the work done.

II. METHODS OF INVESTIGATION

A. Introduction

The funding limitation imposed on the project provided very little time for the principal investigators. Accordingly, the approach to the problem which was finally adopted was aimed at making the most efficient possible use of the available time. This consisted of conducting a quick look investigation of the ERTS images as they arrived, in order to determine those which were most worthy of further examination, and to decide on which methods of study might be most promising for our purposes. In addition, an effort was made to acquire and organize data from other sources within the limits of available funds. The purpose was to avoid using more investigator time than necessary until near the end of the contract period when the maximum amount of data would be available for study.

B. Data Sources

1. ERTS-1 photographic imagery

Images of all four bands were obtained in the form of 70mm positive and negative transparencies together with 9 x 9 inch photographic prints at a scale of 1:1,000,000. These data were requested regardless of cloud cover because the 4000m mountain tops of interest sometimes protrude through clouds, with tops at say 3000m, which completely cover other parts of the scene. Table 1 lists all images used in this study. Following Scene 38 (13 Aug 1973, 1386-20220) we no longer obtained images with heavy cloud cover.

TABLE I

ERTS-1 imagery used in the study of Wrangell Mtns. Alaska (49 scenes) together with one scene over Mt. Erebus in Antarctica.

Scene	Date	NASA image number	Sun elev.	Approximate cloud cover	Mt. Wrangell Summit	Copper Glacier Terminus	Comments
1	2 Aug 72	1010-20331	43°	5%	V	NV	CP, 4A
2	18 Aug 72	1026-20220	39°	10%	NV	V	
3	19 Aug 72	1027-20275	39°	80%	NV	NV	
4	20 Aug 72	1028-20333	38°	60%	V	V	CP
5	5 Sep 72	1044-20221	33°	80%	NV	V	
6	6 Sep 72	1045-20273	32°	70%	NV	NV	
7	6 Sep 72	1045-20280	32°	70%	PV	NV	
8	7 Sep 72	1046-20332	31°	60%	V	NV	CP, 4B
9	23 Sep 72	1062-20221	27°	0%	V	V	M, CP
10	24 Sep 72	1063-20273	25°	0%	V	V	M, 4C, 6B
11	24 Sep 72	1063-20280	26°	0%	V	NIS	M
12	25 Sep 72	1064-20331	25°	20%	V	V	M
13	11 Oct 72	1080-20222	20°	100%	NV	NV	
14	12 Oct 72	1081-20275	18°	10%	V	V	M, 4D, 6C
15	12 Oct 72	1081-20281	20°	5%	V	V	M, CP
16	13 Oct 72	1082-20333	18°	40%	NV	PV	
17	31 Oct 72	1100-20335	12°	30%	V	V	
				End of 1972 scenes			
18	6 Mar 73	1226-20342	20°	45%	PV	V	
19	22 Mar 73	1242-20232	27°	100%	NV	NV	
20	23 Mar 73	1243-20284	27°	80%	NV	NV	
21	23 Mar 73	1243-20291	28°	90%	NV	NV	
22	9 Apr 73	1260-20232	34°	70%	NV	V	
23	10 Apr 73	1261-20284	34°	5%	NV	V	

Scene	Date	NASA image number	Sun elev.	Approximate cloud cover	Mt. Wrangell Summit	Copper Glacier Terminus	Comments
24	10 Apr 73	1261-20291	35°	40%	NV	NIS	
25	27 Apr 73	1278-20232	40°	60%	PV	V	
26	28 Apr 73	1279-20290	41°	30%	PV	PV	
27	15 May 73	1296-20231	45°	30%	V	PV	
28	16 May 73	1297-20285	46°	70%	NV	NV	
29	2 Jun 73	1314-20230	49°	80%	NV	NV	
30	3 Jun 73	1315-20284	49°	60%	V	NV	
31	20 Jun 73	1332-20224	50°	90%	V	NV	
32	21 Jun 73	1333-20280	49°	30%	NIS	V	
33	21 Jun 73	1333-20283	50°	30%	V	NV	
34	8 Jul 73	1350-20223	48°	10%	V	V	
35	9 Jul 73	1351-20275	47°	10%	V	V	CP, 4E, 6A
36	9 Jul 73	1351-20282	48°	40%	V	NIS	
37	26 Jul 73	1368-20222	45°	20%	V	NV	4F
38	13 Aug 73	1386-20220	41°	80%	PV	NV	
		Official end of data coverage for NASA Task II Project 110-M					
39	14 Aug 73	1387-20275	41°	40%	V	NIS	4G
40	2 Sep 73	1406-20325	33°	40%	V	NV	4H
41	18 Sep 73	1422-20212	29°	0%	V	V	very good
42	7 Oct 73	1441-20264	21°	60%	V	NIS	4I
43	24 Oct 73	1458-20202	15°	10%	V	V	
44	25 Oct 73	1459-20260	15°	20%	V	NIS	
45	12 Nov 73	1477-20260	10°	1%	V	NIS	

End of 1973 scenes

Scene	Date	NASA image number	Sun elev.	Approximate cloud cover	Mt. Wrangell Summit	Copper Glacier Terminus	Comments
46	27 Feb 74	1584-20180	18°	5%	V	V	3, 6D
47	1 Mar 74	1586-20290	17°	0%	V	V	
48	18 Mar 74	1603-20232	25°	2%	V	V	
49	5 Apr 74	1621-20230	32°	15%	PV	NIS	
		End of ERTS-1 data supplied to University of Alaska					
50	24 Dec 72	1154-19322	24°	0%	Mt. Erebus and other peaks of Ross Island, Clear-Summit Crater and Fang Ridge of Mt. Erebus are snow-free.		

Abbreviations used in Table I,

V = Visible
NV = Not Visible
PV = Partly Visible
NIS = Not in Scene
CP = Computer printout available (see Fig 5)
M = Mosaic prepared
4A, 4B... = Scene partly shown in Figure 4A, Figure 4B...etc.
5A, 5B... = Scene partly shown in Figure 5A, Figure 5B...etc.

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2. Digital tapes

Digital tapes, requested for six of the 49 Wrangell Mountain scenes listed in Table I, are identified in Table II.

TABLE II

Digital tapes obtained for six scenes with computer print-out prepared for summit region as indicated.

Scene	Date	Sun el	NASA Number with band printed
1	2 Aug '72	43°	1010-20331-4
			1010-20331-5
			1010-20331-7
4	20 Aug '72	38°	1028-20333-7
8	7 Sep '72	31°	1046-20332-7
9	23 Sep '72	27°	1062-20221-5
			1062-20221-7
15	12 Oct '72	20°	1081-20281-7
35	9 July '73	47°	1351-20275-7

3. Aerial Data from NASA Aircraft NP3 during 1972

NASA aircraft NP3 obtained imagery over the Wrangell Mountains in July 1972. This consisted of stereo photography in color and color IR, simulated ERTS imagery, and data from the RS-14 IR Scanner. The data are all from Mission 209 and identified in Table III.

TABLE III

1972 data from NASA aircraft NP3, Mission 209

1972 date	Roll No.	Film type	camera
17/18 July	13	Color Positive	RC8
17/18 July	14	Color IR	RC8
20 July	19	Color Positive	RC8
20 July	20	Color IR	RC8
20 July	23	Color Positive	RC8
20 July	24	Color IR	RC8
22 July	15	Simulated ERTS (±)	KA62
22 July	16	Simulated ERTS (±)	KA62
22 July	17	Simulated ERTS (±)	KA62
22 July	18	Simulated ERTS (±)	KA62
21 July	48	Thermal I.R. B&W(±)	RS-14
18 July	51	Thermal I.R. B&W(±)	RS-14

(±) indicates that both positive and negative film are available

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4. Aerial Photography, 1973.

Navy Aircraft obtained black and white stereographic photography together with I.R. Scanner data over the Wrangell Mtns. on 24 July 1973.

5. Charter flight, 1973

On 9 July, 1973, a flight was made over the summit to make direct observations and to acquire color photography with a hand-held camera at the same time that the satellite was passing overhead. The ERTS scenes 35 and 36 (see Table I) were made at this time.

6. Field trip to summit 1973

From 25 to 30 Aug 1973 a field trip was made from Fairbanks to the summit of Mt. Wrangell. Topographic profiles established during 1965 and 1966 were resurveyed in the North Crater. Ash temperature profiles were measured and photographs were obtained from ground control points. The cost of this trip was paid by the State of Alaska and by the Principal Investigator (vacation time).

7. Additional photographic data

Photography from private collections was assembled together with the purchase of some 1957 aerial photography from the U. S. Geological Survey.

C. Procedures

All imagery acquired by the ERTS-1 satellite over the summit of Mt. Wrangell, regardless of cloud cover, was requested from NASA. In some instances, images with cloud cover approaching 100% provided useful information. This is because the area of interest is small relative to the total area covered by the imagery, and/or because the cloud tops lie below the altitudes of interest. The best examples of this are in scenes 8 and 31 (Table I, also scene 8 is partly shown in Fig 4B). All imagery was examined to determine its usefulness in terms of the features visible. The images were numbered in chronological order and logged onto a master list (Table I). A notebook was prepared with a description of each of the 50 scenes. Mosaics at a scale of 1:1,000,000 were prepared from scenes 9, 10, 11, 12 (23 to 25 Sept 72) and from scenes 14 and 15 (12 Oct '72); see Table I for identification of scenes. These mosaics provided base maps which proved valuable study aids in combination with a wall map at scale of 1:250,000 made by assembling the USGS topographic quadrangles Gulkana, Nabesna, Valdez and McCarthy (Fig 1).

1. Unenhanced ERTS-1 images

The features studied in this research can be separated into two groups: (a) detailed features at the summit of Mt. Wrangell, and (b) general features of glaciers throughout the Wrangell Mountains, including: snowline altitudes, moraines and drainage areas adjacent to the glaciers.

The distinction of cloud cover from snow proved to be a minor problem only. Clouds could usually be recognized by the presence of associated shadows, by the presence or absence of known bare rock areas, and by comparison of images from successive, overlapping passes.

(a) Summit region. The main features of the summit region (Fig 2) consist of three craters, 0.5 to 1.0 km in diameter, along the rim of the 4 x 6km oblong, ice-filled caldera. These features are described in section III and it will suffice at this point to indicate that they are easily identified on all unobscured images. In general the summit area is unresolved on bands 4 and 5, because the contrast between large areas of bright reflecting snow and small areas of dark exposed rock was so great that the latter were masked. Band 7 was most satisfactory, and band 6 was also adequate. However, when the NASA enhanced prints became available during the spring of 1973, the utility of the prints for our purposes decreased somewhat, because the sharpness of the boundary between snow and rock on the imagery was reduced on all bands.

Of the 38 images which came with project No. 110-M the summit region was discernable as follows:

discernability	No. of images	%
visible	18	47.5
not visible	15	39.5
partly visible	4	10.5
not in scene	1	2.5
TOTAL	38	100.0%

The summit region was visible on ten (and partly visible on the eleventh) of the eleven images which came to the University of Alaska ERTS library after the termination of data for Project 110-M on 13 Aug 1973. The reason that the summit was so readily visible on the latter images but only on 47.5% of the ones which came with project 110-M, was due to the difference in cloud cover requirements. The U of A ERTS library acquired images for all of Alaska which had less than 20% cloud cover. On the other hand Project 110-M took all images including those with 100% cloud cover. This maximum tolerance for cloud cover proved valuable because the summit was clearly visible on 14 images with more than 20% and in one case up to 90% cloud cover as follows:

TABLE IV

Useful summit scenes with more than 20% cloud cover

Scene No. (See Table 1)	NASA No.	% cloud cover	Discernability of summit area
4	1028-20333	60%	Visible
8	1046-20332	60%	Visible
17	1100-20335	30%	Visible
18	1226-20342	45%	Partly visible
25	1278-20232	60%	Partly visible
26	1279-20290	30%	Partly visible
27	1296-20231	30%	Visible
30	1315-20284	60%	Visible
31	1332-20224	90%	Visible
33	1333-20283	30%	Visible
36	1351-20282	40%	Visible
38	1386-20220	80%	Partly visible
39	1387-20275	40%	Visible
40	1406-20325	40%	Visible

The most significant thing about the images of summit region is that one can clearly identify changes in the amount of bare rock exposed on them. The variations can be ascribed to the deposit of new snow from storms, some of which were observed in progress on images with thick and variable cloud cover. The melting of this snow again exposes bare rock in specific areas on the crater walls and rims. Volcanic heat is the only source of heat for this melting. We have determined this by ground observations. Thus, because of available images from repeated passes, we are able to observe changes at the summit of Mt. Wrangell which are clearly caused by the volcanic heat flux. This is discussed further in Section III.

(b) General glacial features in the Wrangell Mountains. Snow line around the Wrangell Mountains could be mapped easily from the ERTS imagery, so that patterns of snow-fall and melt could readily be detected. The distinction between snow, firn, and ice on glaciers flowing off the Wrangell Mountains can also be made from the imagery. Band 7 is best for this purpose. Snow appears white, firn is generally light gray, and ice a noticeably darker gray. These identifications were verified by comparison with air photos. There is a problem in defining these boundaries accurately when the glacier surface is steep so that the horizontal extent of the exposed firn is not great. In that case, the bright reflection from the snow tends to mask the firn, and the boundaries cannot be determined.

It was also possible to identify features of glacial outwash flooding at the terminus of glaciers. The best example is at the terminus of Copper Glacier. In this case the utility of using all four bands of ERTS imagery was clearly apparent.

2. Color Additive Viewer

An International Imaging Systems (I^2S), Color Additive Viewer is available through the University of Alaska ERTS Data Library, and the utility of this instrument for enhancement of the imagery for the purposes of this project was investigated. In general, the conclusions are similar to those above for the viewing of unenhanced images. The resolution of the photographic products are not improved by the viewer, so the lack of detail visible at the summit still limits the utility of this product. However, snow line is easily recognizable on the viewer, and registration of imagery from different satellite passes provides an especially useful and immediate identification of changes of snow distribution patterns between passes. In addition, this equipment uses the undodged 70mm positive transparencies, and thus, the problems associated with using the dodged prints are eliminated.

3. Digital data print out

Contouring of density levels on computor print-outs of the digital data of selected images provided the most accurate method of defining the area of exposed bare rock at the summit of Mt. Wrangell. In this procedure, a number or letter is assigned to each pixel of the data according to its density level, following the scheme: "0" for levels 0 to 9, "1" for levels 10 through 19, and so on. The letters "A, B, and C" refer to the levels 100 to 109, 110 to 119 and 120 to 127 respectively. Contouring, done directly on the computer print-out, yields maps of the summit area on a scale of about 1:20,000. For high contrast scenes, contouring of band 7 appears to give the most detail. However, for low contrast areas or scenes, band five is superior. This conclusion has been verified by comparison of contoured print out of data from both bands for several scenes. It has been determined that it is possible to infer outcrops of bare rock within shadow areas within the active crater by contouring print out of band 5.

As noted above, air photos were acquired over the summit in July of 1972 and 1973. Both these flights were made within two weeks of satellite passes on which good data over the summit area were acquired. In addition, the 1973 field trip to the summit followed the flight by about one month. These data provide an excellent opportunity to test the accuracy with which the print-out contouring technique can be used to detect differences in snow cover at the summit. Contoured digital print-outs of the summit area were prepared for the relevant satellite passes, and overlayed on prints of the air photos for each year. Differences in exposed rock area were apparent on the photography, and the recognition of these changes on the contoured digital data was easily done. The feasibility of monitoring changes in activity at the summit by this method thus seems to be established.

The data described above were all acquired during periods when the sun angle was high. As the sun drops, however, shadows at the summit become deeper, and the interpretation becomes more difficult. However, the data can still be made usable for the monitoring function by calculation correction factors for the reflectivity of the surface for various sun angles. Topographic maps of the summit are available from which slope angles can be calculated, so that the approach is feasible. Availability of such a correction procedure would permit the data obtained at low sun angles to be utilized more effectively in the monitoring procedure.

Finally, it should be noted that there is a degree of distortion in the computor print-out, which results from two factors: 1) the difference in the shape of the area representing each pixel on the original data, and 2) the fact that the computor print-out positions each pixel directly in line with that preceding it along the satellite path, thus eliminating the skewness which is evident on the photographic products of the data.

Experiments aimed at transferring contoured print-out from the computor paper to an undistorted base using a zoom transfer scope have been made. The process is tedious but straight-forward, and the contours can be transferred as desired.

4. Digital Color Display Unit (CDU)

Only a preliminary evaluation of the applicability of this unit to the project objectives was accomplished due to limitations on the capability of the system which have not yet been corrected. However, the results suggest that the CDU may provide the most efficient means of obtaining the desired results, for the same reason that the contouring of digital data was successful. That is, the CDU illuminates one point of light on a color TV screen corresponding to each pixel, with the appropriate density represented by a discrete color selected by the operator. Thus, the CDU can be utilized to duplicate the pixel by pixel display of density levels which to date have been generated by hand contouring.

The display of the digital data on the TV screen is at too small a scale to be useful for the purposes of this project. However, the possibility of programming the display so that each pixel of the data is represented by a cluster of light points on the screen is being considered. If this is possible, then the scale of the display will be increased to a usable level.

The television display suffers from the limitation that the image tends to be even more distorted than the digital print-out. However, this deficiency can also be corrected through the use of the zoom transfer scope.

Finally, the CDU display is well suited to picking boundaries between snow, firn and ice.

III RESULTS OF INVESTIGATION

A. Introduction

As noted, the primary purpose of this project was to conduct a feasibility study of the applicability of ERTS data to the problems outlined above. However, results of interest, some of which go beyond the original scope of the project, were obtained and are briefly reviewed in this chapter.

The Wrangell Mountains (Fig 1) are especially interesting because of the interaction between volcanic heat and glaciers and because they "...are mantled by the most compact glacier system in Alaska. This is partly due to elevations locally exceeding 16,000 feet (approx. 5000 m), to a topography that favours extensive cover of upland ice, and to somewhat lower coastal mountains to the south and southwest" (Sharp 1956, p. 101). The continuous glacier-covered area in the Wrangell Mountains is slightly more than 5000 Km^2. We shall discuss some general glacier features of these mountains after first examining the active summit of Mt. Wrangell.

B. Summit Region

1. General Description

The summit of Mt. Wrangell (Fig 2) consists of a 4 x 6 km oblong, ice-filled caldera with craters along parts of its rim. The snow surface in the caldera is relatively flat, varying from 4000 to 4100m in about 3.5km along a SE to NW direction. There are three prominent craters along the rim.

(a) Active Crater. The diameter of this crater is about 0.5 km. An area of about 250,000 m^2 on its north inner wall is bare of snow, except for brief periods immediately following heavy snowfall; this wall also has several sets of active fumaroles. During some years (1966 especially)

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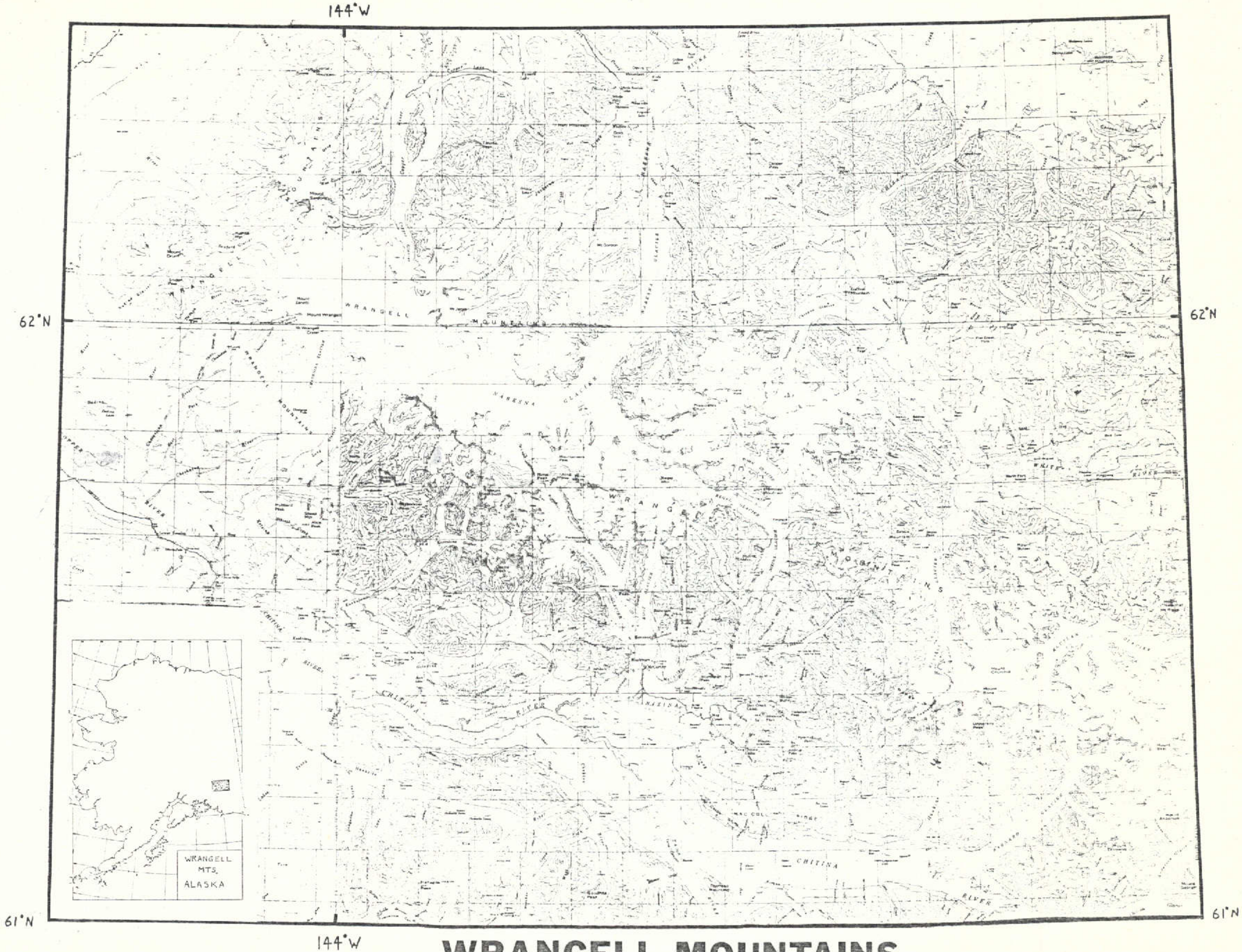
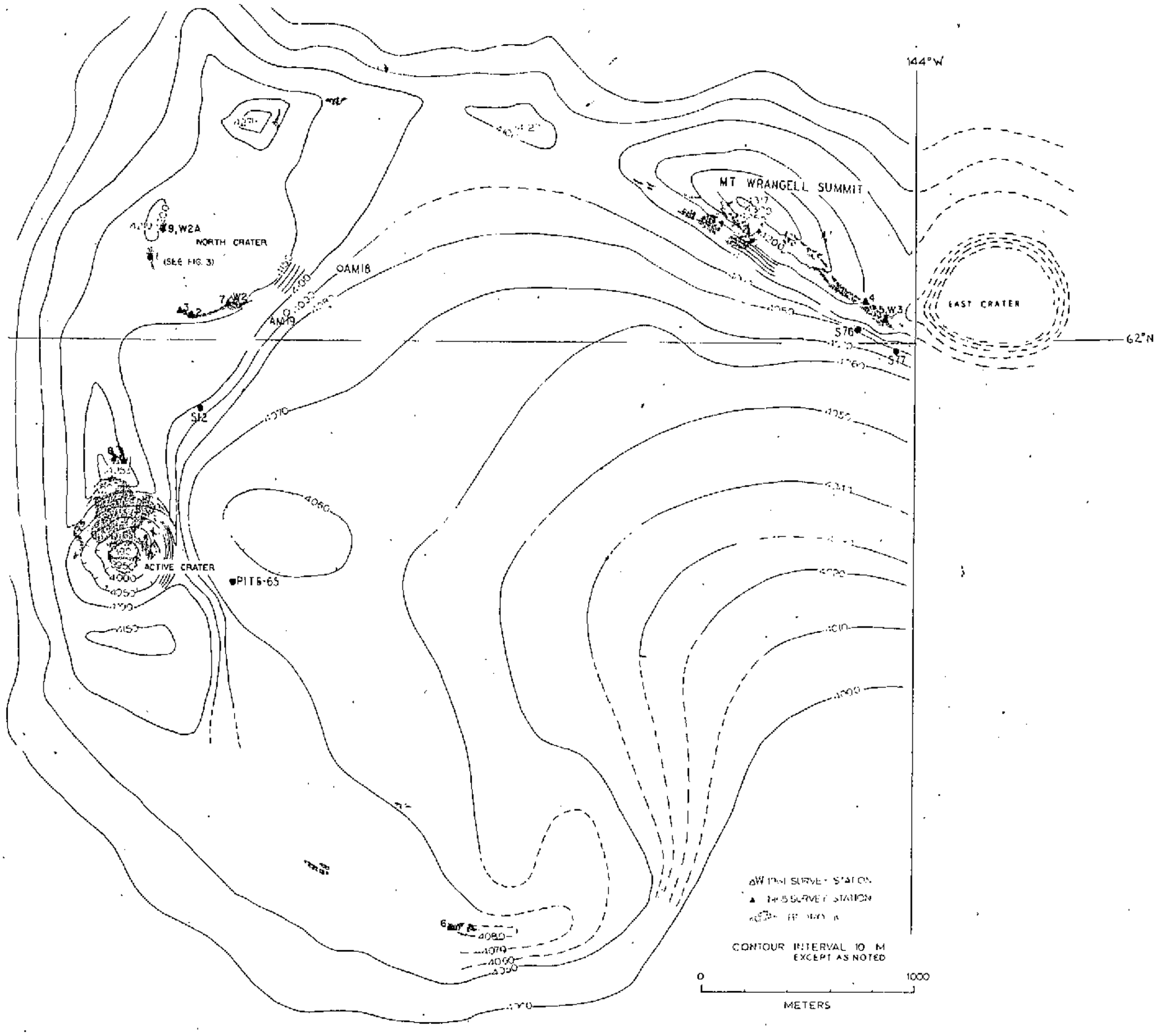


WRANGELL MOUNTAINS, ALASKA

Figure 1



MT. WRANGELL SUMMIT

Figure 2

the active crater has had a lake at its bottom. It has been active throughout the 20 years for which we have direct observations. The active crater is one of the most distinctive summit region features and it can be easily identified on all unobscured ERTS images. It is identified in Figure 3 and the arrows in Figures 4 and 6 point to it.

(b) North Crater. The North Crater lies north-northeast of the active crater and has a diameter of about 1 km. "Hut Ridge" forms its southern rim and until 1966 this was the only snow-free rim of the crater; our research stations have been located on Hut Ridge near the points 2 and 7 on Figure 2. The volcanic activity of the North Crater has increased markedly during the decade 1964 to 1974. The bare rock rims of this crater are now 20 to 100 m wide and linearly continuous along 1 to 3 km around the perimeter. The map in Figure 2 was made in 1965 and shows the longest exposure on Hut Ridge to be less than 500 m long. This crater is as easy to identify on unobscured ERTS images (Fig.3) as is the active crater. Because of the rapid changes occurring in it, it has been an object of special attention as we examined ERTS images.

(c) East Crater. The East Crater is located at the top of a fairly symmetrical cone almost directly east of the North Crater. It is about 0.5 km in diameter and much less active then the other two craters, with less exposed rock around its perimeter. However, the ridge connecting it to the summit peak (Fig 2) is quite active with many fumaroles as well as large areas which are kept snow free by volcanic heat. This crater is identifiable on all unobscured ERTS images (Fig 3), but not as readily as are the two other craters.

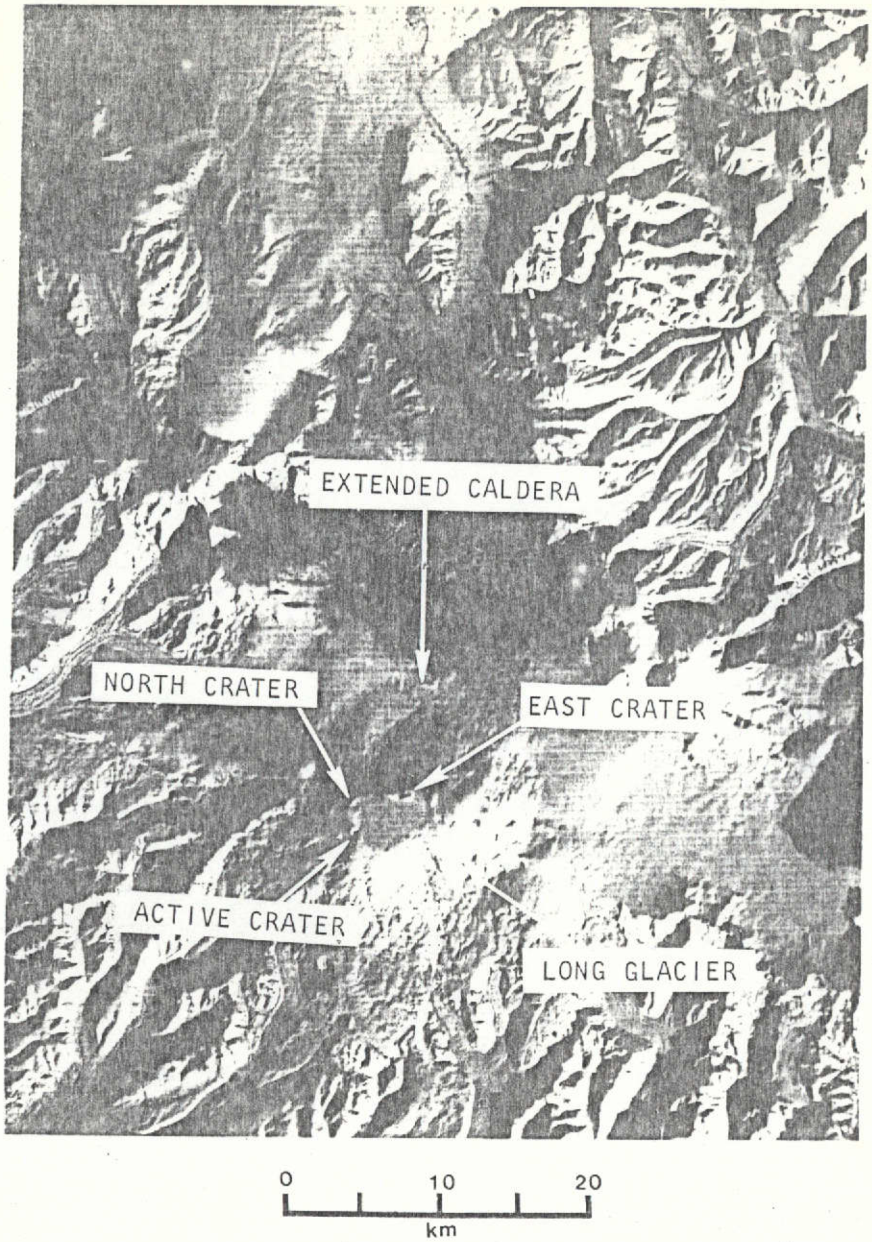


Figure 3 ERTS Resolution of Mt. Wrangell:

This is a portion of ERTS image 1584-20180-7, 27 Feb 1974, Sun el 18°; the main features of the summit caldera, shown in detail in Figure 2, are identified on it. The tip of the arrow labeled "Extended Caldera" points to what appears to have been the outer edge of a much larger caldera (see text).

2. ERTS Photographic Images

Figure 3 is an enlarged part of scene 46 in Table I (27 Feb. 1584-20180 Sun el 18°) it shows Mt. Wrangell with the main features of Figure 2 identified on it. This is by no means the best image of the summit region. Although the low sun elevation makes features at the summit (especially the East Crater) easy to identify, it causes heavier shadows than are desirable. The main purpose of Figure 3 is to serve as a link between Figures 2 and 4, and to identify the extended caldera which is discussed below. The Copper Glacier extends north from Mt. Wrangell and passes under the word "caldera" in this figure. It is too dark to be seen easily in this figure and is clearly identified in Figure 6A.

One of the outstanding features of the ERTS system is its repeated coverage of a given area. This has proved especially useful in identifying the deposition of new snow from storms (in some cases we can observe the progress of the storms, since we get images regardless of cloud cover) and subsequent melting of the snow by volcanic heat. Several examples of this will be discussed with the aid of Figure 4.

(a) Figure 4A. Figure 4A is part of the image of 2 Aug 1972 (Scene I-1)*; it shows the North, East and West walls of the active crater to be free of snow. One snow patch is visible along the South wall and from ground observations this is known to frequently extend to the bottom of the crater. The North Crater has bare rock exposed around most of its perimeter; this is a far more extensive exposure of bare rock than was present in 1965 when the map of Figure 2 was made.

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*For brevity, scenes will be referred to by their numbers in Table I, thus scene 2 of Table I is identified as "Scene I-2".

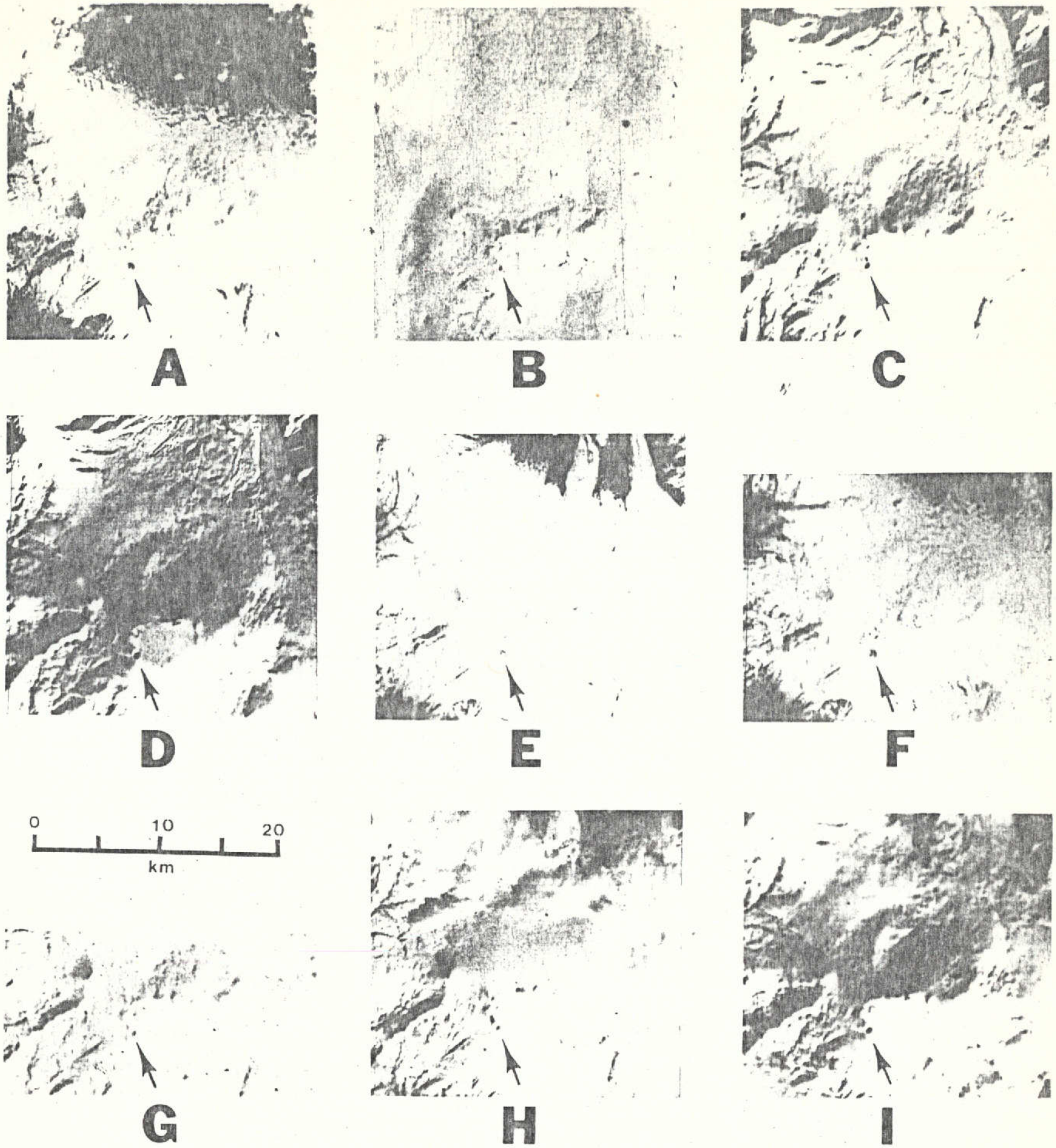

Figure 4. ERTS images of the Summit Region of Mt. Wrangell. The arrows point to the active crater (see Fig 3).

A,	2 Aug 72	1010-20331-7	Sun el 43°	B,	7 Sep 72	1046-20332	Sun el 31°
C,	24 Sep 72	1063-20273-7	Sun el 25°	D,	12 Oct 72	1081-20275	Sun el 18°
E,	9 Jul 73	1351-20275-7	Sun el 47°	F,	26 Jul 73	1368-20222	Sun el 45°
G,	14 Aug 73	1387-20275-7	Sun el 41°	H,	2 Sep 73	1406-20325	Sun el 33°
I,	7 Oct 73	1441-20264-7	Sun el 21°				

On 18 August '72 (Scene I-2) high clouds covered the summit of Mt. Wrangell and it appeared that a storm was beginning. On 19 August '72 (Scene I-3) a major storm was in progress with thick cloud patches oriented in waves roughly 60 to 70°T. On 20 August 1972 (Scene I-4) the summit area was free of clouds. However, new snow covered the inner walls of the active crater and all but one spot on the rim of the North Crater. All of the distinctive dark areas of Scene I-1 are absent on Scene I-4. The active crater was identified mainly by the shadow on its south wall.

(b) Figure 4B. The summit region was covered by clouds on 5 and 6 Sept. (Scenes: I-5, I-6 and I-7) and barely showed through the clouds again on 7 Sept. in scene I-8 (Fig 4-B). Although the summit above 3000m was above the clouds, the rest of the mountain was completely obscured. The part of Scene I-8 shown in Figure 4-B, indicates that significant snow accumulation occurred during the storms of late August and early September 1972. It covered the walls of the Active Crater, the East Crater and Summit Ridge as well as most of the North Crater rim. There appears to be one small dark area on the east part of Hut Ridge (near W2 on Fig 2) which represents bare rock. We know from recent field work that this is the hottest part of the North Crater. The contrast between Figures 4A (2 Aug) and 4B (7Sept) clearly shows the effect of new snow in covering bare rock outcrops.

(c) Figure 4C. In Figure 4C, from Scene I-10 of 24 Sept 1972, one can identify dark areas on the rim of the North Crater and on the north wall of the Active Crater. There also is a black area immediately north of the Active Crater. This is near points 8 and W1 (Fig 2) on the caldera side of the ridge extending north from the Active Crater; it is a place where bare ground has been occasionally observed during the course of our field work in the summit region. The net effect of volcanic heat in melting snow and exposing bare ground at the summit of Mt. Wrangell is clearly displayed by contrasting Fig 4B (7 Sept) with Fig 4C (24 Sept). We are certain of this interpretation because volcanic heat is the only possible way for this melting to have occurred; this is known from field work at the summit during summer and fall months of previous years (Benson, 1968; Wharton, 1966).

(d) Figure 4D. Figure 4D from scene I-14 of 12 Oct 1972, shows an interesting zig-zag pattern on the northeastern side of the North Crater. This pattern is due to the pattern of exposed bare ground which has been emerging--especially since 1968. It shows on the photos taken by NASA aircraft NP3 on frame 0040 of rolls 19 (color positive) and frame 0040 of roll 20 (color IR) taken in July 1972. The same patterns are present on other images--for example it is apparent on Figs 4E, F, G, H and I, (especially 4F). It is also clearly displayed in the Navy photographs of 1973 as well as in our photographs from both ground and air in 1973. The fact that this pattern is visible on the ERTS images is significant because it allows us to follow, in more detail, the ongoing emergence of the North Crater from its snow cover. This is a long-term process; it has now extended over 5 years and seems to be accelerating. In addition to this we can observe the short-term changes associated with individual snow storms.

As a final comment on Figure 4D it is interesting to note how fortuitous it was that we could get it at all. On the preceding day (11 Oct, Scene I-13) there was 100% cloud cover with waves, elongated in a direction 60°T, across the entire scene. On 12 Oct (Fig 4D) the weather was exceptionally clear--to the extent that a mosaic was made of adjoining images (Scenes I-14 and I-15) extending from 60° to 64°N. On 13 Oct

(Scene I-16) the weather deteriorated markedly and the Wrangell Mountains were completely obscured. This incident by itself indicates the exceptional utility of the ERTS program. During a one-day window in stormy fall weather it provided a useful image of the entire Wrangell Mountains. Furthermore, the image contained useful details which indicated several changes at the summit: (1) The dark patch, exposed on the inner side of the ridge north of the active crater on 7 Sept (Fig 4C) was covered by new snow on 12 Oct, (2) The volcanic activity in the North Crater exposed the zig-zag pattern between 7 Sept and 12 Oct (3) The fact that the zig-zag pattern was exposed in the north crater during the same time that the bare patch north of the active was covered indicates that the North Crater is the site of most activity at present. This has been verified from field observations, but the fact that it can be observed directly on 1:1,000,000 ERTS images is exciting!

(e) Figure 4E. Figure 4E, from Scene I-35 of 9 July 1973, was made as we were observing and photographing the summit region from a small airplane in our flight which was timed to coincide with the satellite pass. The summit was cloud-free as were the mountains in general except for a few scattered cumulus clouds at lower altitudes. Bare rock areas were well exposed all around the North Crater as well as on the inner walls of the Active Crater. The flight allowed us to confirm observations made on the ERTS images. In particular, it provided us with an opportunity to observe directly the progress of the significant changes which are going on in the North Crater. Since weather conditions were so exceptionally good on 9 July 1973, with large exposures of bare rock around the rim of the North Crater, it seems surprising that the ERTS image, partly shown in Figure 4E, did not show the North Crater in sharper contrast. It may be that the brightness was so great (47° sun elevation) that it swamped out some of the dark areas.

(f) Figure 4F. Figure 4F, from Scene I-37 of 26 July 1973, shows the North Crater to be slightly more exposed than it was in Fig 4E of 9 July. This is most likely due to a wider band of exposed rock along the west rim. It may also be, in part, due to the slightly 2° lower sun angle since both the inner walls of the active crater and the rim of the North Crater appear darker on the 26 July image (Fig 4F) when compared to the 9 July image (Fig 4E).

(g) Figure 4G. Figure 4G, from Scene I-39 of 14 August 1973, shows the summit region covered by new snow. The inner walls of the Active Crater and most rim areas of the North Crater are snow covered. The dark areas on the southeast and east part of the North Crater appear to be exposures of bare ground, but it is difficult to be sure because of shadows at least in the southeast part. Nevertheless, it is obvious that on 14 Aug new snow covered much of the bare ground area which was exposed on 26 July. Some of this snow probably came from the storm which was still active and serving to obscure the summit region on Scene I-38 of 13 August. Snow also fell during the time between 14 and 28 August when we landed on the summit between the Active and North Craters. Indeed, the snow fall delayed our trip by making flying weather impossible between 24 and 28 August. On 28-31 August new snow was observed to be melting away from parts of the North Crater rims. It was also present along the ridge between the Active and North Crater which had been bare on 24 Sept 1972 (Fig 4C).

(h) Figure 4H. Figure 4H, from Scene I-40 of 2 Sept 1973, shows a large bare area (about $125{,}000m^2$) on the ridge between the Active and North Craters. The melting which exposed this area took place during the two days between our direct observations on 30 Aug and this scene of 2 Sept. Again this illustrates the capability of ERTS imagery to follow detailed changes in the summit region which are reactions to individual snow storms.

(i) Figure 4I. Figure 4-I, from scene I-42 of 7 Oct 1973, shows heavy snow cover on all parts of the summit. Shadows make interpretations difficult, but there appears to be a cloud visible in the SE part of the North Crater which is due to the vapor discharged from active areas on the inner rim of the crater. Clouds of this origin have frequently been observed in the course of our field work at the summit. However, some dark areas in the center of the North Crater may be due to the crevasses which are developing there as a result of the marked settling of the surface. This interpretation also agrees well with the pattern seen on Scene I-46 of 27 Feb 1974 (Fig. 6D).

3. Digital Data Printout

The photographic images at a fixed scale of 1:1,000,000 discussed above are extremely useful and certainly constitute the most widely used product of the ERTS program. However, photographic processing of the data includes some inherent shortcomings as well. These are due to the lumping of data from several pixels in making the photographic image and from variability in the photographic processes. The ultimate resolution of data is the direct digital printout of each pixel in a selected region.

Figure 5 was made by contouring density levels on digital print-out of ERTS data over the Active Crater and the North Crater. Figure 5A compares band 7 from the six scenes listed in Table II. The Active Crater is the roughly circular feature in the lower part of the drawings. The North Crater is in the upper part and generally has an open place in the eastern part of the rim. Figure 5B shows the difference between band 5 and band 7 for the data of 23 Sept 1972 (1062-20221; Scene I-9). Although band 7 only goes up to density levels in the 6 range, usually to level 65, it is the best one for high contrast scenes. In Figure 5A the broken pattern on the east rim of the North Crater shows up well on the images from 2 and 20 Aug 1972 and 9 July 1973. It is caused by a break in continuity of the exposed rock on the rim. Glacier ice extends across the rim at this point. On the north rim of the North Crater the dark pattern has two centers of maximum intensity with the eastern part offset slightly to the north. This is a good representation of a slight offset in the exposed rock area on the northwest rim which shows clearly on the aerial photographs taken by NASA in 1972 and by the Navy in 1973. The exposed rock extends farther towards the crater in the Western half

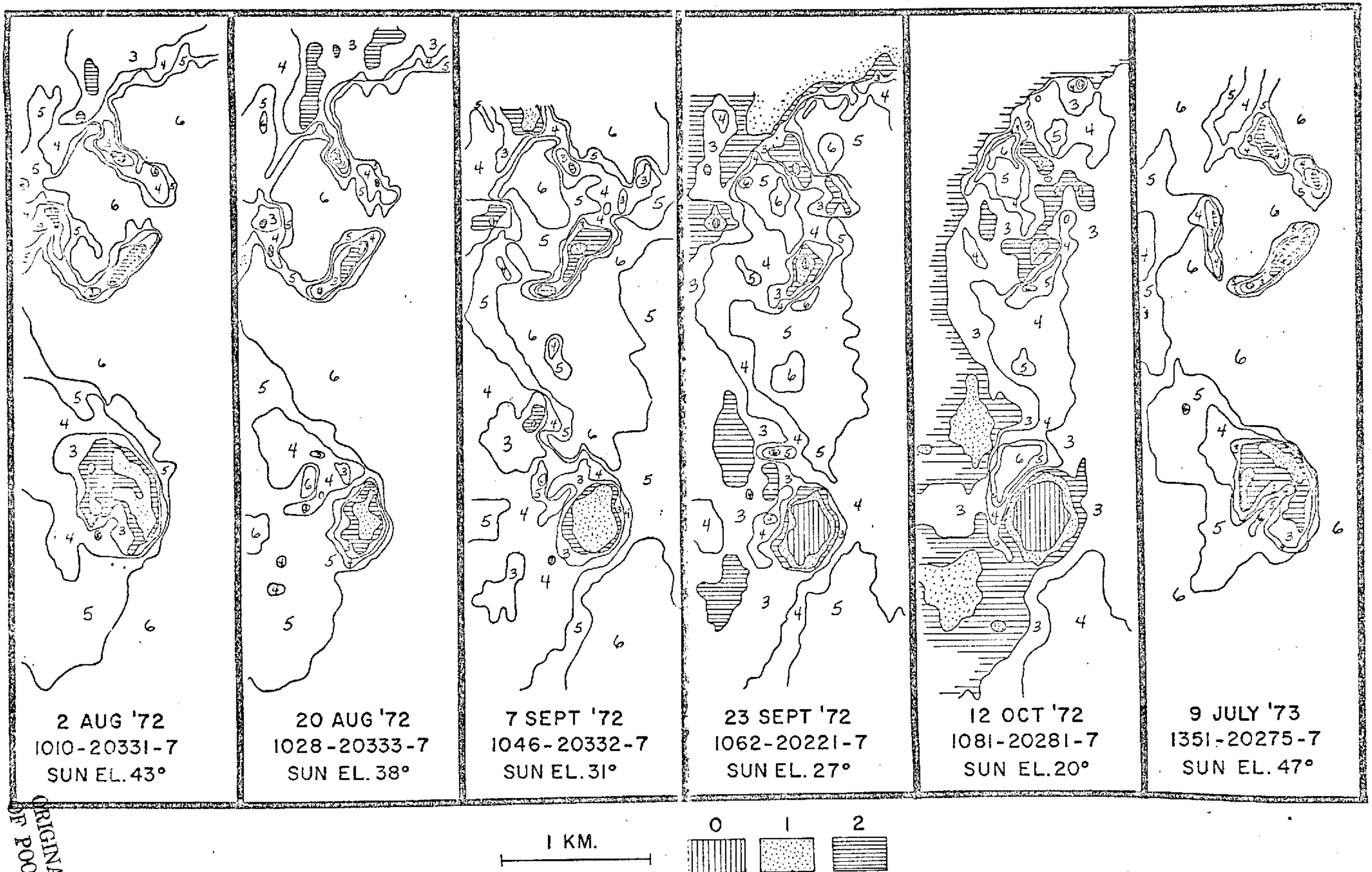

Figure 5A Contoured Digital Printouts of Band 7.
The North Crater is at the top, the Active Crater is at the bottom. The number scheme is: "0" for levels 0 through 9, "1" for levels 10 through 19, and so on to "9" for levels 90 through 99; the letters A, B, and C refer to the levels 100 through 109, 110 through 119 and 120 through 127, respectively.

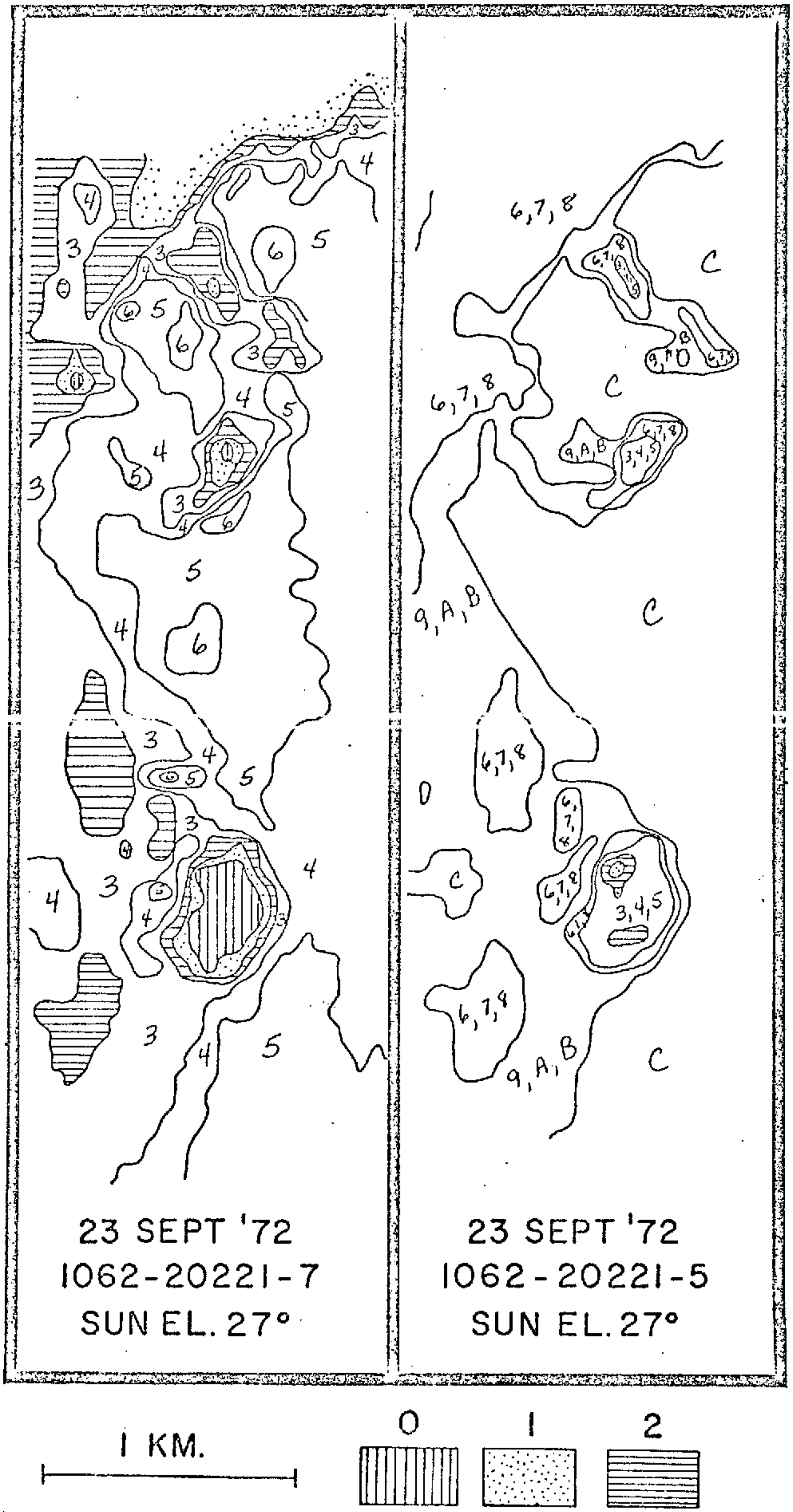

Figure 5B Contoured Digital Printout Comparison of Bands 5 and 7.

of the northern rim. The digital printouts permit one to map the features of these craters at a scale of about 1:20,000. As pointed out in Chapter II, when the aerial photos are projected on top of the digital printouts, one can interpret the printouts in detail.

For example:

(1) The snow patch in the southwest part of the active crater shows clearly in the printouts for 2 Aug 1972 and 9 July 1973.

(2) The amount of bared area at the northern end of the North Crater's rim has increased from 2 Aug 1972 to 9 July 1973. This is a useful record of the increased exposure of the North Crater during a one year interval.

In some cases band 5 in superior to band 7. A comparison of bands 5 and 7 for the data of 23 Sept 1972 (1062-20221, Scene I-9) is shown in Figure 5B. Heavy shadows were present at the summit (see Fig 4c). On band 7 the Active crater is uniformy dark at levels 0, 1 and 2 largely because of shadows. On band 5 one can find darker areas in places where exposed rock are expected to occur in the active crater. Also, the outline of the North Crater on band 5 resembles its pattern on the band 7 data from 2 and 20 Aug 1972 and 9 July 1973. The data from both bands are useful in this case, it makes the complex pattern in band 7 easier to interpret. Band 5 and 7 are complimentary in the sense that band 7 shows levels only up to 65 whereas band 5 shows very small areas below the 60 level and concentrates on the levels from 60 to 127. Band 5 seems best suited for locating outcrops of rock exposure in shadowed regions. In general, the feasibility of observing interactions between snow and ice and volcanic heat at the summit by this technique seems well established.

C. Glacier Features in General

1. Moraines

Among the most striking features of glaciers in the Wrangell Mountains are the moraine patterns. The Russell Glacier, lying east of Chitistone Pass, has a well developed wavy pattern to its medial moraine which suggest that it has undergone several surges. It is the only glacier in the Wrangell Mountains to show evidence of surging.

2. Debris-cover

Some glaciers of the Wrangell Mountains are especially laden with debris. This is especially true of the Sanford and other glaciers flowing from Mt. Sanford, for the Kuskulana Glacier wich flows in several branches from Mt. Blackburn, and for the Nadina Glacier from Mt. Drum. The exceptional amount of debris on these glaciers may be the result of catastrophic activity such as land slide, avalanche combinations in the steep-walled upper cirque areas. A study on the origin of this anomalous debris-cover should be undertaken. It may shed light on glacier response to variations in lithology and structure, and to tectonic and volcanic activity.

3. Snow Line

Snow line data are available for some glaciers. However, it proved to be difficult to follow variations in snow line as a function of time for several reasons. One of the major problems is that clouds frequently obscure parts of the glaciers during July and August when maximum snow-line altitudes are expected. Also, it proved difficult to identify snow line on some glaciers which have steep, south-facing (i.e., sun-facing) slopes directly in the critical altitude range through which the snow line varies.

In general the snow lines begin to rise on glaciers of the Wrangell Mountains in May and reach maximum altitudes in late July and through mid-

August. The maximum altitudes appear to be slightly higher on the north-facing glaciers. This may be interpreted as an indication of heavier snow accumulation on south-facing glaciers since they directly receive the main storm winds which bring new snow whereas the north-facing glaciers are on the lee side of the major accumulation sources. However, this interpretation requires verification. The snow line descends rapidly in late September and early October to the terminal regions of all glaciers in the Wrangell Mountains.

In 1972 few data were available since the first image was received on 2 August and snow line had descended to the terminus of all glaciers by 24 Sept (Scene I-10). Of the ten available scenes six did not permit snow line determinations on any glaciers. The best 1972 image for determining snow line altitudes is Scene I-2 of 18 Aug (1026-20220). It shows the snow line on the north-facing Nabesna Glacier to be at 6600 ft.* on the east branch and 7000 ft. on the west or main branch. A small lake is present on the ice at 6800 ft. altitude immediately east of a nunatak in the main branch. The snow line on the south-facing Kennicott Glacier is about 4900 ft. which is significantly lower than that for the Nabesna Glacier. As mentioned above this may indicate heavier snow accumulation on south-facing glaciers since they face into the main storm winds which bring new snow.

In 1973 more data were available and the best images for snow line determination are those of Scenes I-34, I-35, I-37 and I-41 from 8, 9 and 26 July and 18 Sept respectively. The first evidence of ablation on the Kennicott and Nabesna Glaciers is on Scene I-26 from 28 April. It shows moraines on the Kennicott Glacier from the terminus at 1400 ft. up to 2500 ft., to be nearly free of snow. These moraines are exceptionally

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*Altitudes in this section are given in feet because the available contour maps are still printed in Medieval units.

debris-covered and this may contribute to the early snow melting on them. On the Nabesna glacier this image shows a slightly grey area which appears to be ablation of new snow in the altitude range of 4200 to 5700 ft. The lowest part of the glacier, from 3000 to 4200 ft. is white, except for the main medial moraine. It appears to have less melting, this may be due to thicker snow as a result of katabatic winds, which move snow from the upper region, mentioned above which is fairly straight and subject to wind erosion, to the lower part of the glacier. Such an interpretation should be field-checked.

Scene I-30 from 3 June 1973 (1315-20284) shows the Nabesna Glacier covered by new snow except for the main medial moraine which was bare up to 5800 ft. This is the result of storms in May and this image itself was 60% cloud cover. On 21 June ablation was exposing moraines on the Nabesna Glacier at the 6000 to 6500 ft. range.

On 8 July 1973 Scene I-34 (1350 20223) snow lines are well displayed as follows: Nabesna 6100, Kennicott 4200, Gates 5000, Root 5000, Rohn 4900, Regal 4400 (all values in feet). The Long Glacier snow line was 5500 to 6000 ft. on Scene I-36 from 9 July.

The maximum snow line altitudes observed on 1973 ERTS images were on Scene I-37 of 26 July (1368-20222). These show snow lines on several glaciers as follows: Nabesna, 7200 ft.; Chisana, 6900 ft.; Russell, 6700 ft.; Long, 6700 ft. (questionable estimate because of steep slope); the Kennicott Glacier was obscured. As in 1972 the maximum altitudes appear higher on the North facing glaciers (Nabesna and Chisana).

On 18 Sept 1973, Scene I-41 (1422-20212) is especially clear and shows a significant descent of the snow line on all glaciers. The snow line altitudes are as follows: Nabesna, 4800 to 5000 ft.; Chisana 6500 ft. and Long Glacier 4600-5000 ft., and Rohn, 5600 ft. The next available scene (I-42) of 7 Oct 73 (144-20264) was too cloud covered to provide snow line data, but it did reveal that the Kennicott Glacier was snow free below 2800 ft. On Scene I-43 of 24 Oct 73 (1458-20220) the snow line extended to the terminus of every visible glacier.

4. Drainage features of glacial outwash plain

At the terminus of the Copper Glacier during the summer a large black area on band 7 suggests that a lake is present. This shows clearly in Figure 6A from 9 July 1973. During the fall this feature disappears with the exception of two dark areas, one in contact with the glacier and the other one several km downstream from it. This shows well in Fig 6B from 24 Sept 72. Between 24 Sept and 12 Oct the two open areas froze (Fig 6C). The true nature of the broad dark area and the two dark centers which remain longest during freezeup can be determined by examining data from other bands and from the aerial photos which were taken in July 1972.

Bands 4 and 5 of 9 July (1351-20275) show the broad dark area of Band 7 (Fig 6A) to be slightly lighter in color than most of the tundra but not as light as the stream channels. However, when this region is compared to lakes such as Copper Lake and Tananda Lake it is definitely not a lake. Indeed, even on band 7 the broad dark area near Copper Glacier is not as dark as the lakes which are black on the band 7 image. On band 4 of 1351-20275 (9 July 73) two light colored areas coincide with the two dark patches of Fig 6B from band 7 of 24 Sept 72 (1063-20273). These light areas have the same appearance as the surfaces of Klutina and Tonsina Lakes on band 4 of image 1351-20282 which directly follows 1351-20275. This indicates that these two patches are silt-laden lakes in the outwash plain. The extended dark area of band 7 on Fig 6A apparently is caused by the watersoaked flood plain which is laced with small streams as seen on the aerial photographs especially frame 0129 of Roll 23 NASA Mission 209, July 1972. This photograph shows the two lakes on the flood plain and the clear boundary of the

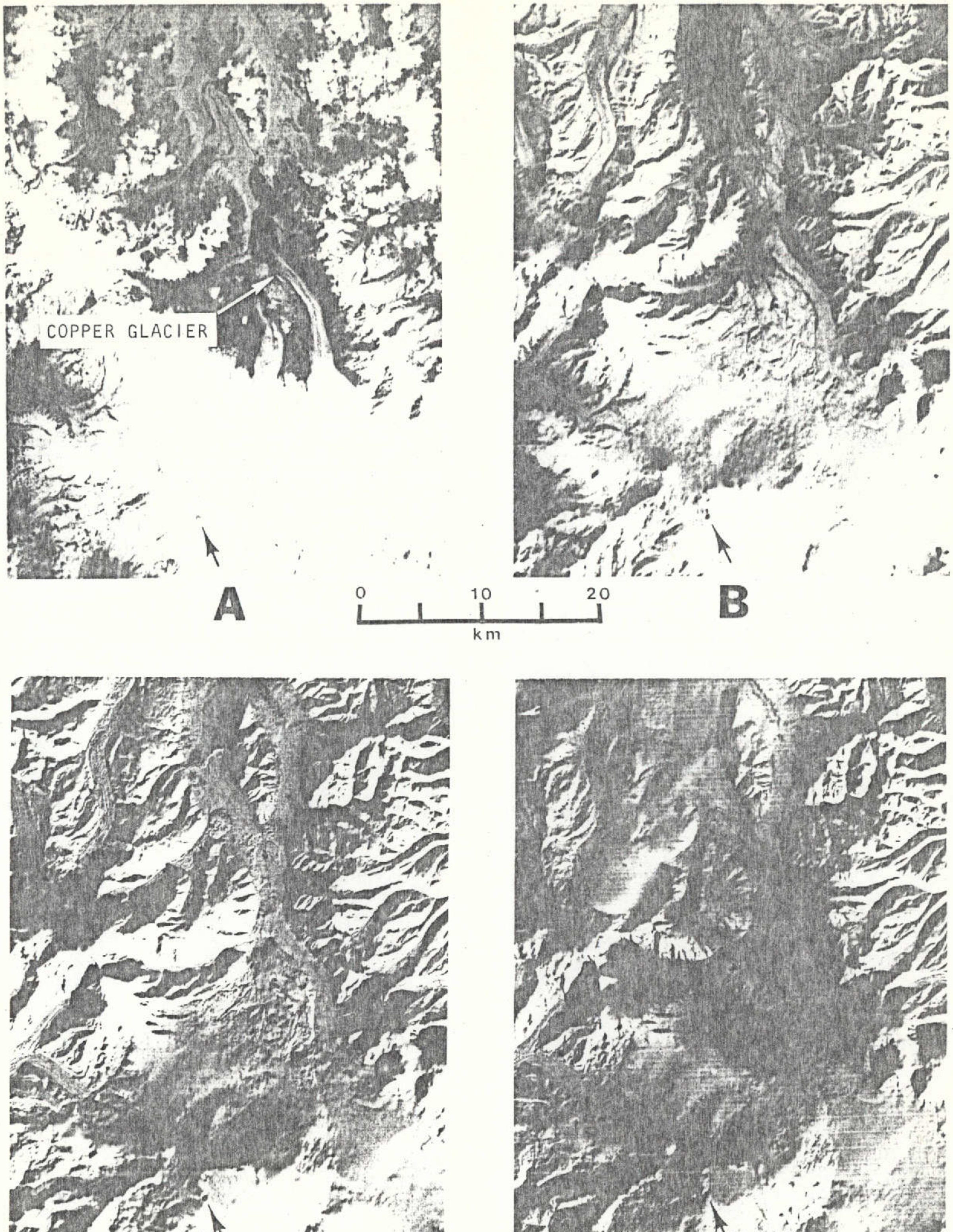

Figure 6 ERTS Images of Mt. Wrangell and Copper Glacier. The arrows point to the active crater (see Fig 3).

A, 9 Jul 73 1351-20275-7 Sun el 47° B, 24 Sep 72 1063-20273-7 Sun el 25°
C, 12 Oct 72 1081-20275-7 Sun el 18° D, 27 Feb 74 1584-20180-7 Sun el 18°

floodplain in contact with surrounding areas which are covered by vegetation.

The surface is frozen in both Figures 4C and 4D. However, Figure 4D from 27 Feb 1974 (1584-20180-7) is of special interest because of the dark area in the flood plain downstream from the glacier. This area appears dark on all four bands. It represents the open water of an active overflow which will soon freeze to form part of an aufeis deposit (Holmgren and Benson, 1974). It was fortuitous to observe this overflow while it was wet because at this time of year it should be expected to freeze quickly. River overflow phenomena and the resulting aufeis deposits are common in Alaska. However, this phenomenon has not been studied in the Wrangell Mountains. None of the other glaciers in the general area of the Wrangell Mountains showed this activity directly on the available ERTS images. It is tempting to associate the origin of the winter flood water in this case with volcanic heat from Mt. Wrangell. This association seems especially reasonable because the extensive winter overflow and aufeis deposits of the Ivishak and Echooka Rivers on the Arctic Slope of Alaska are caused by hot springs (Holmgren and Benson 1974). The phenomenon of winter drainage as a result of volcanic heat requires detailed study in the Wrangell Mountains.

5. Effect of Volcanic Heat on Glaciers?

As a final observation of special interest we note the relative absence of glacier ice on the west side of Mt. Wrangell. In general, the Wrangell Mountains have many long, well developed glaciers in the eastern part of the range. However, from the Long Glacier extending south from Mt. Wrangell to the Sanford Glacier northwest of Mt. Wrangell (Fig 1), there are relatively small glaciers such as the Chetaslina. These do not fill their cirque valleys to the extent that the larger glaciers do in the eastern part of the range such as Kennicott, Long, Regal, Rohn etc. This may be due to increased basal melt rates from volcanic heat of Mt. Wrangell. A more detailed study of this phenomenon is necessary.

D. Extended Caldera

On Figure 3 there is an arrow pointing to what we refer to as the "extended caldera". This was first noticed on ERTS images with low sun angle. The fact that ERTS obtains repeated coverage of the same area with variable sun angle is extremely useful. The present summit caldera, with craters around its rim, appears to be the southern, highest, and latest active part of a caldera which had a diameter of about 22 km. The northern rim of this extended caldera lies near the labeled arrow tip in Figure 3. The inner part of the rim shows as a light area, because it slopes toward the sun, within the shadow of the summit on Figures 4C, 4D, 4I and 6B, 6C, 6D. It shows exceptionally well in the color composite image of Scene I-17 from 31 Oct 1972; 1100-20335. One can also see a "double ring" on images with sun elevation less than 20°. Note the light area directly beneath the tail of the arrow tip labeling East Crater on Figure 3. This is just inside of the outer rim of the Extended Caldera.

The Extended Caldera was first identified on ERTS images, but it also shows up on images from the NOAA 2 and NOAA 3 satellites which have resolution of 1 km. The "Extended Caldera" is clearly visible as a set of concentric rings on the NOAA 3 image from 26 March 1974 (orbit No 1737 V2). The present summit caldera shows only as a bright spot which interrupts the continuity of the rings on their south side. The NOAA 3 image from 7 May 1974; 2257 V2 also shows the rings of the "Extended Caldera" but less distinctly because of the higher sun angle.

There is also indication of the Extended Caldera in the complex crevasse patterns on the northeast side of Mt. Wrangell. Once one knows where to look for the Extended Caldera it is also apparent on the topographic map of the Wrangell Mountains (Fig 1).

E. Volcanic Heat Flux

During our visit to the summit in late August of 1973 we surveyed 12 points on the western part of the North Crater from control points 2 and 7 (Fig 2) of 1965. The vertical components of glacier flow vectors were anomalously great in the North Crater during the early 1960's, and Bingham (1967) ascribed this to non-equilibirium basal melting by volcanic heat. The observations since then have confirmed this interpretation. Our measurements in 1973 could only be made in the western half of the North Crater because the eastern half had become too complex and dangerous to traverse. We measured a downward vertical displacement of 20 m for the snow surface in the western part of the North Crater. Using these measurements, together with estimates of the surface displacement in the rest of the crater, an order of magnitude calculation has been made of the amount of ice melted at the base of the glacier in the North Crater. From the ice loss it is possible to calculate the heat flux. The order of magnitude calculation was carried out as follows:

(1) The inner radius of the North Crater is approximately 400 m, this gives an area of $\sim 5 \times 10^5$ m^2.

(2) Approximately 1/2 of this area has settled 20 m

Approximately 1/3 of this area has settled 30 m

Approximately 1/5 of this area has settled ~~50~~ 100 m

(3) Combining (1) and (2) yields a volume loss of $\sim 20 \times 10^6$ m^3 or 18×10^9 Kg of ice.

(4) If we assume the temperature of the ice at the ice-rock contact point to be 0°C and use 80 cal/gm for the latent heat of fusion of ice, it would require 144×10^{10} Kcal to melt this amount of ice.

(5) The actual heat required would be greater than this amount since the mean annual temperature is -20°C. If we assume that the ice started at this temperature we may use an "effective latent heat" of 90 cal gm^{-1} which yields a value of 162×10^{10} Kcal for the heat required.

(6) By estimate (4) we obtain 2.9×10^{6} Kcal m^{-2} and by estimate (5) we obtain 3.2×10^{6} Kcal m^{-2}, for our purposes the value 3×10^{6} Kcal m^{-2} is adequate.

(7) Since this was over a time span of 8 years we obtain a heat flux of about 1200 μcal $cm^{-2}sec^{-1}$.

The average geothermal heat flux for the planet is between 1 and 2 μ cal $cm^{-2}sec^{-1}$. Thus, the heat flux in the North Crater is 10^{3} greater than the earth's overall average value. This applies to the entire North Crater and is close to the values calculated for bare ridge areas in 1961 and 1965 (Benson, 1968; Bingham 1967). These order of magnitude calculations will be improved when we obtain more detailed information on the amount of ice melted in the summit area together with temperature profile measurements in the sand and ash of the exposed ridges.

IV. CONCLUSIONS

The interaction between glaciers and volcanic heat has been studied by remote sensing over Alaska's Wrangell Mountains in general and at the 4000 m summit of Mt. Wrangell (62°N; 144°W) in particular. Short term changes at the summit of Mt. Wrangell, produced by the depositon of snow and subsequent melting of this snow by volcanic heat, can be observed directly on ERTS images at scale of 1:1,000,000. The use of digital printouts, from band 7 for high contrast scenes and band 5 for low contrast scenes, yields maps of the summit region at a scale of about 1:20,000 with sufficient detail to follow significant changes.

Band 7 is generally the best one for these studies. However, it is useful to compare several bands when working with digital print outs of specific regions at the summit and when using photographic images in the drainage areas. The feasibility of using ERTS for this work has been established. Indeed, we have already gone beyond the feasibility stage as outlined in Chaper III. The need for continued study with a broader scope is outlined in Chapter V. In particular, it is necessary to make more use of digital maps of the summit, and to carry out an extensive aerial photogrammetry program together with ground truth measurements.

V. RECOMMENDATIONS

The study of glaciers and volcanic activity by remote sensing should continue in the Wrangell Mountains. This is especially important because of the increasing volcanic activity which is currently underway at the summit of Mt. Wrangell. The snow and ice cover on the volcano serves as an effective calorimeter in addition to making surface features easily observable. The summit and surrounding region have attractive potential from the point of view of geothermal energy and, of course, there is a potential hazard which must be monitored.

All satellite imagery over the Wrangell Mountains should be obtained and cataloged, regardless of cloud cover. The value of this has been demonstrated.

Digital print-out of all data for the summit craters should be made and maps should be prepared from them.

Aerial photographs, suitable for photogrammetry, should be made over selected sites every year as long as the present rates of change continue at the summit. The next step needed in this operation is the establishment of ground control points for aerial photogrammetry on the rims of the three craters as well as on the summit ridge. These control points should be photographed as soon as they are established so that controlled stereographic models can be made. Once this is done, the control points can be used on subsequent aerial photographs and on photographs taken at earlier dates as well. Maps should be made of the caldera in general and of the North Crater in particular from the aerial photographs every year. The caldera should be mapped at a scale of 1:10,000 with a 10 m contour interval; the North Crater should be mapped at a scale of 1:2,000 with a 1 m contour interval.

Suitable photographs are available from 1972 and 1973 as mentioned in Chapter II; we have also contracted to have a set of photographs made in 1974 by an Alaskan firm. It is necessary to establish the above mentioned ground control points before maps can be made from these photographs.

A map of the existing glacier outlines throughout the entire Wrangell Mountains should be constructed from ERTS imagery, and reviewed periodically for changes in glacier size and shape.

Seismic stations should be established at the summit and along the flanks of Mt. Wrangell.

Heat flux measurements should be made in the Wrangell Mountains in general as well as at the summit.

Thermometers installed at the summit should be equipped to transmit data, along with the seismic signals--either to ground communication lines or to satellites.

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VII. PUBLICATIONS (from this project)

Benson, C. S. 1973

NASA, Snow Cover Surveys in ALASKA from ERTS-1 Data Symposium on Significant Results Obtained from the ERTS-1

Volume 1 Technical Presentations Section B p. 1593-1595

VIII. REFERENCES (cited in this report)

Beiser, A., 1953. Mt. Wrangell Expedition, Physics Today, Oct 1953, p. 10-14.

Benson, Carl S., 1962. Reconnaissance Snow Studies on Mt. Wrangell, Alaska, Bull. American Meteorological Society, Vol. 43, p. 140.

Benson, C. S., 1963. Reconnaissance Snow Studies on Mt. Wrangell, Alaska. Geophysical Institute, University of Alaska, Final Report prepared for CRREL under Contract No. DA 11-190-ENG-131, 38 pp.

Benson, C. S., 1967. Polar Regions Snow Cover, in: Physics of Snow and Ice, Proceedings of the International Conference on Low Temperature Science, 1966, Volume 1, Part 2. The Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan, p. 1039-1063.

Benson, C. S., 1968. Glaciological Studies on Mt. Wrangell, Alaska, Trans. A.G.U., Vol. 49, p. 167.

Benson, C. S., 1968. Glaciological Studies on Mt. Wrangell, Alaska, 1961, Arctic, Vol. 21, No. 3, p. 127-152.

Benson, C. S., D. K. Bingham, R. B. Forbes, J. Kienle and G. B. Wharton 1965, Wrangell Mountains, Alaska, Annual Report, 1964-65, Geophysical Institute, University of Alaska p. 55-59. (Brief reports on Mt. Wrangell research are cited in Annual Reports of the Geophysical Institute as follows: 1963-64, p. 52-53; 1964-65, p. 55-59, p. 76; 1965-66, p. 58-59; 1966-67, p. 67-69.)

Benson, C. S., and R. B. Forbes, 1965. Reconnaissance Glaciological and Volcanological Studies, Mt. Wrangell, Alaska (abstract), Proceedings of the 15th Alaskan Science Conference, p. 93-94.

Benson, C. S., D. K. Bingham, and G. B. Wharton, 1971. Glaciological and Volcanological Studies at the Summit of Mt. Wrangell, Alaska, Proceedings XV General Assembly, IUCG, Moscow, August 1971 (in press).

Bingham, D. K., 1967. Ice motion and Heat Flow Studies, Mt. Wrangell, Alaska, M.S. Thesis, University of Alaska, 117 pp.

Bingham, D. K., C. S. Benson, and G. B. Wharton, 1967. Glaciological Studies on Mt. Wrangell, Alaska, Part 1--Stratigraphy and Accumulation. Proceedings 18th Alaska Science Conference.

Bingham, D. K., and C. S. Benson, 1967. Glaciological Studies on Mt. Wrangell, Alaska, Part II--Ice Motion and Heat Flow Studies. Proceedings 18th Alaska Science Conference.

Bingham, D. K., and C. S. Benson, 1968. Ash Temperature Variations on Mount Wrangell, Alaska, New Zealand Journal of Geology and Geophysics, Vol. 11, p. 781-786.

Chauvin, D. L., 1965, Field Services, Mt. Wrangell Station, Annual Report 1964-65, Geophysical Institute, University of Alaska, p. 76.

Furst, J. I., 1968, The Reconnaissance Petrology of Andesites from the Mt. Wrangell Caldera Alaska, M.S. Thesis, University of Alaska, 83 pp.

Holmgren, B. and Benson, C., 1974. Aufeis as observed by ERTS, Final Report Conract NAS5-21833, Task 4, ERTS project 110-4.

Sharp, R. P. 1956, Glaciers in the Arctic, Arctic, Vol. 9, p. 78-117.

Treves, S. B. and P. R. Kyle (1974), Volcanic activity of Mount Erebus, 1973-1974, Antarctic Journal of the United States, Vol. IX, No. 4, p. 147.

Wharton, G. B., 1966. Snow Stratigraphy Studies in the Caldera at the Summit of Mt. Wrangell, Alaska, M.S. Thesis, University of Alaska.

White, Donald E., 1969. Rapid Heat-Flow Surveying of Geothermal Areas, Utilizing Individual Snowfalls as Calorimeters, Jour. Geophysical Research, Vol. 74, No. 22, p. 5191-5201.